INTERACTIVE PHYSICAL DESIGN AND HAPTIC PLAYING OF VIRTUAL MUSICAL INSTRUMENTS

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ABSTRACT

In Computer Music, a practical approach of many Digital Musical Instruments is to separate the gestural input stage from the sound synthesis stage. While these instruments offer many creative possibilities, they present a strong rupture with traditional acoustic instruments, as the physical coupling between human and sound is broken. This coupling plays a crucial role for the expressive musical playing of acoustic instruments; we believe restoring it in a digital context is of equal importance for revealing the full expressive potential of digital instruments. This paper first presents haptic and physical modelling technologies for representing the mechano-acoustical instrumental situation in the context of DMIs. From these technologies, a prototype environment has been implemented for both designing virtual musical instruments and interacting with them via a force feedback device, able to preserve the energetic coherency of the musician-sound chain.

1. INTRODUCTION

In the context of digital musical instruments, the number of novel interfaces and control mechanisms for musical creation has greatly increased in recent years. However, few of these systems address the question of the physical and energetic coupling between gestures and sounds. We assume here that: (1) this coupling plays a crucial role in musical instrumental expression and more generally in music, as with traditional musical instruments; and (2) it is only achievable in a digital context by regrouping a number of specific technological conditions, which we will develop. Then, we present a new prototype environment enabling the musician to design his own virtual musical instruments as a whole, from gesture interfaces to vibrating structures by physical modelling and then to physically interact with them via a high performance force feedback device. Our system aims to remain as faithful as possible to a mechano-acoustical instrumental situation, by ensuring the energetic coherence between the human and the sound through the simulated object. First, we situate our motivations in the current state of the art. Then we discuss the technologies and concepts involved, and the work that has been accomplished to create the prototype haptic modeller/simulator for musical creation presented here. Finally, examples of several instruments created and played with this new environment are presented.

2. HAPTICS IN COMPUTER MUSIC

The design and real time playing of Digital Musical Instruments (DMIs) is now a common practice. In most cases, a technological constraint for these instruments is the separation of gestural input and sound production. Mapping strategies are then employed to associate gestural signals to various sound synthesis parameters. However, this breaks the physical coupling between human and sounds that is found in acoustical instruments.

2.1. Uses of haptic devices in computer music

An increasing number of DMIs now employ haptic devices, with various aims. The recent literature can be analysed and categorised according to the different goals and uses of haptics in these digital instruments. Haptic systems are researched-on and used either:

- To convey relevant information about a digital musical instrument to the musician's tactile-kinaesthetic perception, by displaying haptic cues (haptic display). This includes guiding or assisting the user in performing musical gestures [1,11].
- To program the mechanical behaviour of a gestural controller, while maintaining mapping strategies for standard sound synthesis processes. Hence, haptic models can be used to adjust or extend the ergonomics of the gesture device [9,16].
- To physically interact with a simulated instrument, including its acoustical parts, aiming to restore the instrumentality found in acoustic instruments [2,10,14,17]. The present article focuses on this particular situation, which will be further detailed in following sections.

The above classification of the pursued goals also enables functional categorisation of the haptic devices and haptic simulation technologies employed in subsequent systems. In the first two categories, the DMIs are usually grounded on a classic mapping-based architecture between gestures and sounds, extending the gestural control section with haptic feedback. In most cases, this can be relevantly achieved with classic haptic devices and asynchronous simulation architectures [1,16]. The third case, as it contains physical interaction between all the parts of the instrument, from gestures to sounds, implies much harder technological constraints.

2.2. Using haptics for physical interaction with simulated instruments

An instrument can be described as a physical object used by humans to enhance their communication and interaction skills with the rest of the world. The energy injected into the instrument through the user's gestures induces physical and material transformations to the surrounding environment. There is a physical coupling between the user and the instrument, a permanent

energetic flow between the two parties, which intimately correlates the physical output of the instrument to the energy and nature of the human's input gestures. Cadoz defines this as the ergotic function of a gesture [3].
Historically, work targeting to restore instrumentality in the musician-sound relationship began in the 70's at ACROE-ICA and has gained interest in recent years.

In this context, haptic devices are used as a direct interface between the human and a virtual simulated vibrating instrument, aiming to represent a complete instrumental situation between the two.

Immediate and instantaneous physical coupling between a human and a simulated instrument is impossible, as the computer necessarily functions as a causal input/output system. Thus, a digital system of a user manipulating an instrument is composed of two causal sub-systems [4]. Nevertheless, it is possible to ensure the correlation of the inputs and outputs of these sub-systems in order to represent instrumental coupling.

Obtaining a full ergotic action-sound chain implies constraints on the haptic interface and the overall simulation architecture:

- High dynamic response and high peak force feedback from the haptic device, in order to correctly cover the dynamics of the real world instrumental coupling [13].
- A hard real time synchronous simulation loop [13], into which the signals relative to the haptic device are integrated. The simulation rate must also cover the temporal ranges of the entire active and perceptive sensory phenomena at the interface of the user and the virtual object.
- Unicity of the virtual object, through a single physically-based mechano-acoustical model. Thus, the interaction is an audio-haptic physical interaction in the sense that the manipulated sections of the instrument, and further, the gesture, interact bilaterally with the vibrating sections, acting on and receiving physical feedback from each other. Thus, the sound is truly engraved by gestures [14].

This paper showcases an environment for designing physically modelled virtual musical instruments, which can then be simulated and manipulated in real time via a high quality haptic device, building on technologies developed in the following section.

3. EXISTING TECHNOLOGIES

3.1. Technologies for multisensory interaction with simulated objects

ACROE-ICA's research on technologies for real time multisensory interaction with simulated instruments has led to the design of a high performance haptic device, the TGR (*transducteur gestuel rétroactif*) [6,8], which integrates into the ERGON_X multisensory simulation platforms.

The haptic device itself presents a modular slice-based construction, with N one degree of freedom (DOF) keys, which are all equipped with position sensors and electromagnetic actuators for force feedback. Multiple keys can be assembled with a variety of end effectors, such as 2 DOF bows, 3 DOF joysticks, pliers or 6 DOF stylus devices. This versatility enables easy adapting to the diversity of musical gestures.

The ERGON_X platforms interface the TGR haptic device with a TORO DSP Board from Innovative Integration, which runs the high-rate real time physical simulations, including the haptic inputs/outputs.

ACROE-ICA and Grenoble INP currently dispose of two 12 key ERGON_X platforms, each offering 12 DOF with high dynamic response - a unique configuration. Fig.1 shows a 12 key TGR with Piano key end-effectors.

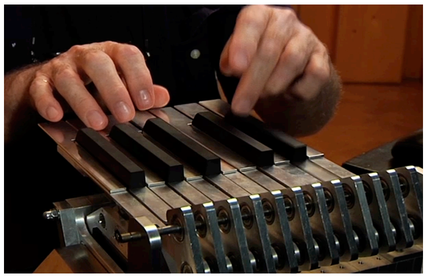

Fig 1. A TGR with a 12 key Piano setup

Many multisensory simulations have been implemented with this technology, including mechanical 2D or 3D objects, musical instruments, and also nanophysics simulations. However, there is no dedicated modeller for the real time platform. All physical models are directly coded in C++ for the DSP. Hence, it is only useable by people with fairly intricate programming skills, which is not necessarily the case for composers and artists.

3.2. Physical modelling for musical creation: GENESIS

The physical modelling and simulation environments developed at ACROE-ICA are implemented upon the CORDIS-ANIMA formalism [4]. It is a modular language for creating and simulating physical objects by building mass-interaction networks based on Newtonian physics. It defines a small number of physical modules that represent elementary physical behaviours, and can be assembled to build complex physical objects. The two main types of modules are:

- <MAT> (mass type modules): punctual material elements, possessing a spatial position and inertia.
- <LIA> (interaction type modules): modules that define an interaction between two <MAT> modules.

GENESIS [7] is the main software environment developed by ACROE-ICA for musical creation with physical models. It possesses elaborate tools to create, edit, and tune physical structures, whose vibratory behaviour generates sound. GENESIS uses a specific implementation of CORDIS-ANIMA:

- Physical objects in GENESIS are designed in a 1D geometrical space, meaning that all <MAT> modules move along a single vibration axis. 1D modelling is sufficient to generate nearly all perceptible aero-acoustic phenomena of vibrating structures [7] and reduces computing and modelling costs.
- GENESIS implements a subset of CORDIS-ANIMA modules, which are relevant for the

creation of vibrating objects, such as masses, fixed points, springs, buffer-springs, viscosity and non-linear interactions.

GENESIS models were, until now, simulated exclusively offline: the simulation engine calculates the evolution of the model from its initial state.

Very large models can be designed, including precisely timed musical gesture metaphors, such as picking, striking, bowing, damping... GENESIS can also encompass compositional metaphors through physical structures, allowing for full musical compositions generated by a single physical model [5]. Therefore, it is not limited to a sound synthesis process; it serves the purpose of a full support for musical creation, based on physical models. Fig.2 shows a GENESIS model encompassing a full musical piece.

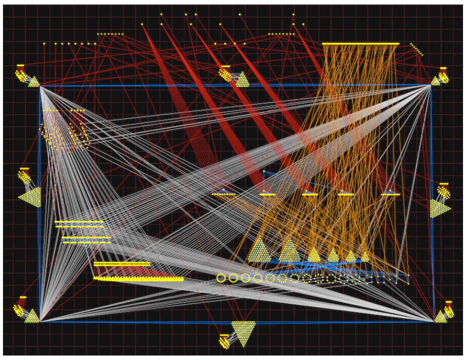

Fig 2. A musical composition created in GENESIS (pico..TERA, by C. Cadoz)

An advanced modelling environment for musical creation, such as GENESIS, and high performance haptic simulation platforms, such as ERGON_X, had never merged so far, due to several technological hard constraints. The presented work addresses these obstacles and combines the two systems, resulting in a prototype modeller/simulator for instrumental interaction with simulated musical instruments.

4. A NEW SOFTWARE ENVIRONMENT

The primary goal for our new real time haptic modelling/simulation environment is to be accessible for the artists themselves, by being as intuitive as possible while allowing full understanding of the physical modelling process and simulation. Our prototype user-centred software environment accompanies the user from designing the virtual instrument to playing it in real time.

First, the user designs a virtual instrument in the GENESIS modelling environment. For instance, he can create one or several strings and tune them to different pitches. He can then create a number of logical representations of the haptic device inside the model and design the various mechanical interactions that he wants with the instrument, such as plucking, bowing, striking or pinching/fretting mechanisms.

Once the model of the virtual instrument has been created in GENESIS, it can be imported into the new real time software environment, shown in Fig.3. At this stage, the user maps the model to the hardware configuration of the TGR haptic device and adjusts the interaction properties between the user and the simulated object.

The last step consists of compiling the model description and the TGR properties into an optimised real time DSP binary application. The user is now ready to launch the simulation, and experiment instrumental playing of the model via the haptic device, including audio and visual feedback.

The simplicity of this whole process allows for an efficient modelling/simulation loop, making the prototyping and experimental testing of new instrument designs very easy for the end-user, even if he has little to no prior knowledge about the underlying technology.

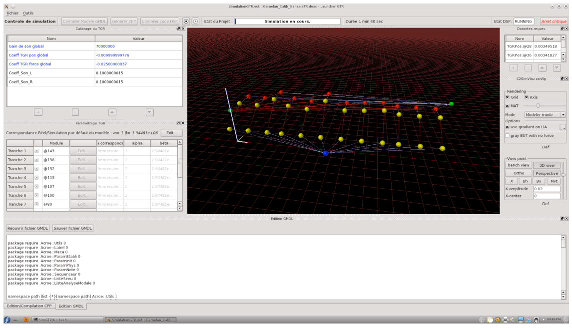

Fig 3. Our new haptic real time modelling and simulation environment

A few haptic modelling/simulation environments for sound exist in the literature [12], though so far none have targeted instrumental interaction. Our work towards a first real time modeller/simulator environment with instrumental interaction has raised several new challenges and questions, including: how can we make real time simulation engine requirements and a modular, high-level modelling environment cohabitate? Which processes are involved for calibrating and defining the representation of a virtual musical instrument in the real world? In the next sections, we will bring forth the solutions we have achieved regarding these challenges.

5. A NEW SIMULATION ENGINE

The CORDIS ANIMA formalism can be implemented in various ways depending on the intended use, e.g. for reactive real time or off-line simulations or with specific adapting to the employed hardware.

For instance, the GENESIS simulation engine is conceived with absolute modularity, meaning that the user can design any physical network he sees fit in the modelling environment, and this model description can be automatically allocated in the simulation engine, then simulated offline.

On the other hand, the ERGON_X simulation engine is designed for maximum simulation speed, on the DSP chip (C6711 from Texas Instruments). The simulation algorithms are coded for a specific model, using vectorised data structures and taking advantage of any regularities in the model's topology and/or physical parameters to optimise the simulation code by hand. Hence, the physical model is tied to the simulation engine, which accounts for the prior lack of a detached and high-level modelling interface.

Simulation constraints for a real time modeller/ simulator include both the above aspects: modular design and synchronous real time simulation on DSP.

We created a bench-testing framework in order to evaluate real time simulation performances of various simulation engines on the DSP chip. Our test methodology featured first measuring the execution time of several basic CORDIS-ANIMA modules (mass, spring and buffer-spring), then simulating a complete musical model deemed representative of user modelling activity and of our expectations for this new platform's performance.

Tests on the GENESIS and ERGON_X engines quickly confirmed our initial impressions: the modularity-driven design of the former excludes any real possibilities of audio-haptic real time simulation, whereas the latter is optimised for real time simulation but is not modular, hence incompatible with our needs.

As a consequence, several new simulator architectures were created and tested using the bench-testing framework, with various data structures, simulation allocation techniques, and expressions of the CORDIS-ANIMA algorithms.

The main factors found to increase the simulation engine's efficiency are:

- Reducing the number of function calls.
- Vectorising the various data structures, including management of the DSP memory specificities.
- Using static memory allocation.
- Optimising the C++ expressions of the CORDIS-ANIMA algorithms for the DSP.
- Excluding all division operations in the critical real time code sections.
- Avoiding the use of conditional expressions.

The result of this work is a new modular, synchronous, hard real time CORDIS-ANIMA simulation engine that runs fully at 44.1 kHz, specifically optimised for the TORO DSP chip. It uses a new data structure, with static memory allocation, and fully reorganises the physical model for vectorised algorithmic computation, using DSP-optimised expressions of the CORDIS-ANIMA algorithms.

Table 1. shows a comparative study of real time performances of various tested simulation engines. The new real time simulation engine is compatible with automatic allocation from a GENESIS model description, allows for completely inhomogeneous topologies and parameters, and yet retains similar performance to the hand-written and non-modular ERGON_X simulation engine.

Our new simulation engine allows for synchronous real time simulation of approximately 100 to 150 modules at 44100 Hz, depending on the type of modules involved (for example, non linear interaction lookup tables are more time-consuming than simple spring interactions). This attainable complexity is sufficient for designing simple yet musically rich instruments, which can use up to 12 of the TGR's keys (e.g. 3 to 4 audio strings with gestural interaction mechanisms, or numerous simpler models).

Table 1. Performance comparison of several simulation engines, executed on the DSP chip.

	Maximum Complexity (nb. of modules vs. simulation sampling rate)
ERGON_X engine	Approx. 200 modules at 44.1 kHz, optimised with homogenous topology and parameters
GENESIS engine	Approx. 20 modules at 44.1 kHz.
New Simulation Engine	Approx. 140 modules at 44.1 kHz, fully inhomogeneous topology and parameters

6. UNDERSTANDING THE REAL WORLD/SIMULATION INTERCONNECTION

Surprisingly, little literature on haptic simulation systems focuses on system calibration and quantitative, measurable real/simulation equivalencies. In the context of instrumental playing of simulated musical instruments, control over the physical properties of the real world, the physical properties of the simulated world, and the interaction between the two is essential.

From a technical perspective, the dynamic response of the TGR haptic device and our physically based synchronous simulation architecture enable full quantitative control of the whole interactive simulation system. However, representing GENESIS instruments in the real world via a haptic interface is new ground. In the following section we explain the implications of haptic interaction with a GENESIS instrument, and then present our work towards full understanding and mediation to the user of the real/simulation haptic interconnection.

6.1. The variety of impedance scales in GENESIS models

GENESIS gives users the freedom of creating physical objects at various physical scales. A minuscule, microscopic object and the same object blown up to a colossal scale can produce completely identical normalised audio output. A real appeal of this freedom of scales lies in the possibility of making various physical scales cohabitate within a single physical model, and in adjusting the retroaction properties between different sub-sections of the model. This can result in complex and rich emerging physical behaviours.

We have deemed essential to allow the user to interact with objects at any scale inside the model, while retaining the energetic consistency of the interaction. This requires representation factors between the real world and the simulation, not only for spatial dimensions but also for impedance. This is a complicated task, as we need to quantitatively define the equivalencies between real world physical parameters and simulated model-space parameters with metrological precision. This concerns haptic device calibration aspects, and also user modelling choices, which are tied to his design choices for each of his GENESIS instruments.

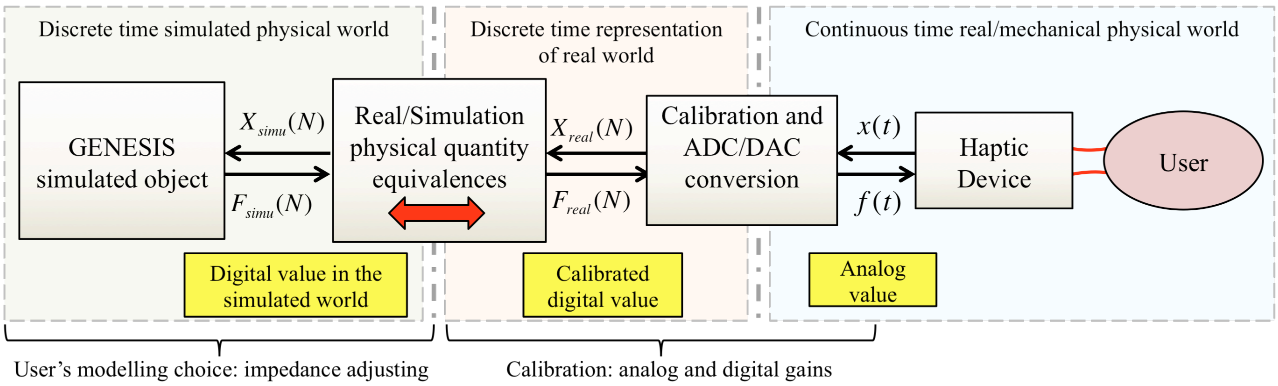

Fig 4. From the user to the simulated object: the full real/simulation loop.

6.2. Space and impedance scales for the haptic devices and users

Haptic devices are designed to operate within a given range, defined by the spatial range of the device and their ability to render stiff behaviour. The ERGON_X platform allows for approximately 20mm of displacement on each 1D axis, and is capable of displaying a stiffness of 40 N/mm [8].

Human gestures, including musical gestures, are also best suited in a given spatial and impedance range. For instance, displacement of a piano key has a spatial range of approximately a centimetre. The impedance of the interaction plays a key role in the playability of the instrument: not feeling sufficient resistance when pressing down the piano key can be off-putting (as often perceived with low-end synthesiser keyboards), whereas a piano requiring a large amount of force to press down each key (very high impedance) would be very difficult (and possibly painful) to play.

All these aspects come into account when designing haptic interaction with real time GENESIS instruments: interaction with the instruments must occur in a range that is suitable for both the haptic interface and the musician's gestures – and further, should take the pursued musical goal into account.

6.3. Quantitative understanding of the real/simulation interconnection

Three parameters define the static mode interconnection properties between the real world and the simulation:

- α the real/simulation position gain.
- β the simulation/real force feedback gain.
- T_e the sampling rate of the simulated world.

These parameters play a double role:

- First, they allow calibrating of the system, ensuring best precision and full control of the position and force feedback signals throughout the whole simulation chain, including compensation of the electronics and conditioning of the position and force signals for optimal precision from the ADC and DAC converters.
- Secondly, they determine the relations between measurable physical quantities of the real world, and physical quantities defined in the simulated model. For instance, in a closed haptic loop the real/simulation static mode equivalency for an inertia is defined by:

$$m = \beta.\alpha.M.Te^2 \qquad (1)$$

Where m is the real world mass, M is the mass value in the simulation world, and α, β and T_e are defined above. Similar equations exist for all other physical quantities.

Fig.4 shows the separation between these two roles. The calibration of the system is an advanced procedure and remains a task for expert users who are familiar with the haptic device. On the other hand, real/simulation impedance adjusting is a modelling choice, to be defined and freely adjusted by the user depending on his simulated instrument. Therefore, it must be mediated in a comprehensive yet complete way in the user interface.

6.4. Mediation to the user

The original ergonomics we propose in our prototype software environment (Fig. 3) separate calibration gains from the physical equivalency adjusting. The position and force calibration gains are determined by completing a dedicated calibration procedure. Once the system is correctly calibrated these values remain valid for all simulations and need only be re-calibrated if the hardware changes or the electronic components in the rack drift over a long period of time.

The modelling choice of the real/simulation equivalencies is presented to the user through a table of static mode physical value equivalencies, shown in Fig.5, displaying all the equivalencies between real world quantities and model-space quantities.

The user never has to manipulate α or β. Instead, the table of physical equivalencies dynamically updates them whenever he sets a specific equivalence for a given physical quantity. For example, the user can define that a mass of 20 (real world) grams is equal to a mass value of 1.0 inside the model, which then computes α and β and updates all other real/simulation equivalencies.

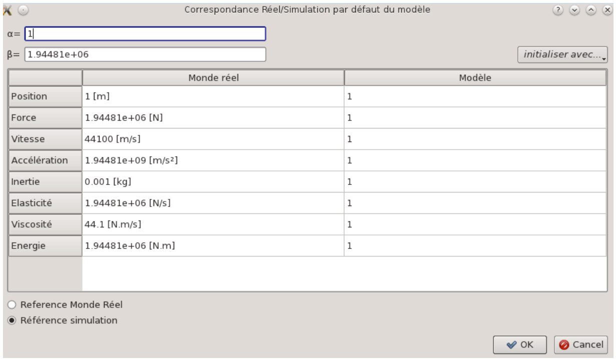

Fig 5. The real/simulation static mode equivalency table for easy impedance adjusting.

Finally, the user may well want to adjust various keys of the haptic device for interactions with different impedance scales inside the model. For this purpose we propose one global real/simulation equivalency as a basis for the whole system, and allow additional per-key fine-tuning with different interaction properties.

This entire procedure allows for complete control of the interaction properties with any GENESIS instrument.

7. MUSICAL CREATION WITH THIS NEW ENVIRONMENT

Our new modeller/simulator gathers all the necessary conditions for playing GENESIS models with energetic consistency. Starting from a strong knowledge base of musical instrument creation with GENESIS [19], the following section demonstrates several examples of real time instruments as well as basic knowledge we are acquiring through engaging in creative activity with this platform. Specifically, we discuss considerations on "haptics in the loop" modelling techniques and the implications of designing single audio-haptic objects.

7.1. Modelling with "haptics in the loop"

In our system, the haptic device directly interfaces the user and the instrument. This brings forth very interesting possibilities for musical creation; however it does introduce new challenges for the modeller.

This direct link means that any imperfections of the haptic device are transferred to the simulated model, potentially all the way to the generated audio signal. The noise on the sensor and actuator signals as well as the temporal delay between the input and output have a negative impact on noise propagation inside the model as well as simulation stability. A critical situation is that of the velocity signal derived from a noisy measured position signal, used for friction models such as the bowed string. Studies have evaluated ways to address this problem at an algorithmic level in the model [17] or by changing methods for obtaining the velocity signal itself at the hardware level [18].

We believe that this situation should be treated both at the software level and the hardware level (through evolution of the haptic device). In the former case, the compromise is to reduce the bandwidth of the noise introduced by the haptic device, while retaining the full instrumental gesture's bandwidth and maximum stiffness.

We propose that the physical modelling paradigm supplies adequate tools for dealing with these issues. For example, physical oscillators can be used to reduce noise from the position sensors, adding a small low-pass filtering stage between the TGR and the instrument it interacts with.

Also, due to the inherent delay of one sample on the TGR's force feedback output, it is preferable to avoid direct viscous interactions with the keys, as the velocity-driven behaviour can be very noisy and potentially unstable. A solution to this issue is to use local damping on connected <MAT> instead of directly introducing a viscous relationship between the TGR and the <MAT>, as shown in Fig.6.

This example demonstrates how we can obtain highly viscous behaviour while avoiding introducing noise, through simple "haptics conscious" physical modelling techniques, which we consider to be very general and that we aim to explore further.

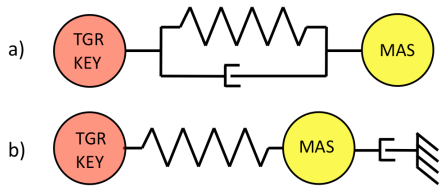

Fig 6. Modelling highly viscous behaviour on the TGR keys: solution a) introduces noise and instability, solution b) filters the TGR sensor noise and allows for very high damping

7.2. A piano-inspired model

Our first model is inspired by the classic piano mechanism. It makes full use of the ERGON_X platform, with twelve individual keys (Fig.7). Each one is connected to a small hammer, which strikes a vibrating structure when the Piano key is moved. Each key is also connected to a fixed point via a buffer-spring interaction, which models the hard contact when the key is fully pressed down. The vibrating structures are simple dampened oscillators connected to a bridge that captures all the vibrations. This reduces the complexity of the model since the DSP computing power is limited when simulating at 44.1 kHz.

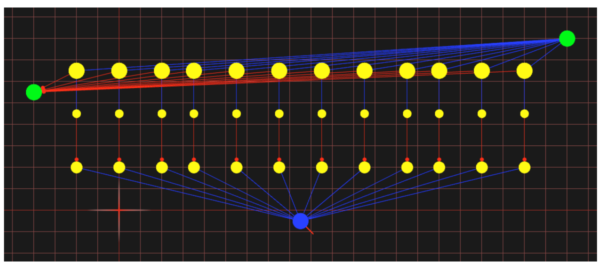

Fig 7. The Piano Model in the GENESIS workbench.

The modelling process encompasses the full design of the instrument: the mechanical feel, as well as the sounding structures. Depending on the complexity of the model, it is possible to adjust the feel of the instrument in a similar way to Gillespie's haptic keyboard [9]. In the above model, the mechanical feel is certainly somewhat simplified, however the real novelty is the full physical connection: the mechanical design and behaviour is intimately tied to the sound and playability, and the instrument is crafted as a whole in consequence.

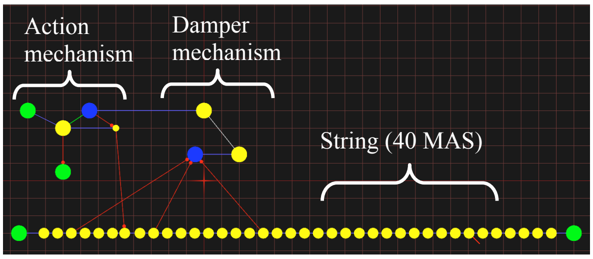

Fig 8. A more complex Piano key mechanism and vibrating structure

A more elaborate Piano key mechanism is shown in Fig.8. It includes a more sophisticated action mechanism, as well as a damper mechanism that mutes the string when the key is depressed. DSP processing power does not currently allow us to simulate a full set of twelve keys with this mechanism and vibrating structure complexity.

7.3. String models

The following instrument is composed of one vibrating structure: a string. Several interaction mechanisms are designed around this string: the user can pluck the string, via a non-linear interaction, damp the string at specific harmonic nodes in order to obtain natural harmonics (Fig.9), and also pinch the string down as one would with a fretting hand, changing the pitch.

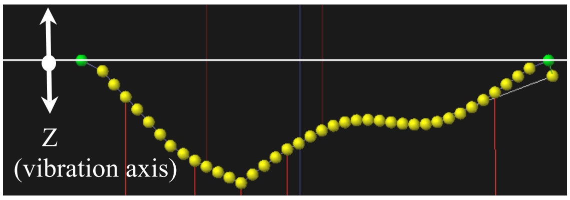

Fig 9. Zoomed-in screenshot of a string model. The string is plucked then dampened at a third of the length, resulting in a natural harmonic a 5th above the open string pitch.

These various actions all influence the resulting sound in a natural yet subtle manner, including non-linear occurrences during the pinching and plucking of the string. These intrinsic physical are phenomena are intimately linked to the energetic coherency of the whole system.

7.4. Continuous excitation models

With the LNL modules (non-linear interactions) in GENESIS we can also design continuous excitation instruments, such as bowed string models. In order to do this we must design velocity driven non-linear interactions with a similar profile to the real world stick-slip interaction of a bow on a string.

Since the space in GENESIS is one-dimensional, simple friction interactions are restricted to the displacement axis and have no pressure parameter. This can be addressed by F. Poyer's work while remaining in 1D [15]. Future perspectives include integrating multiple gestural dimensions into the GENESIS environment, enabling full use of the TGR's diverse end-effectors.

7.5. Designing and playing with unusual physical objects

The above examples show designs inspired mainly by real world musical instrument structures. However, a big strength of physical modelling for musical creation is the possibility to extrapolate starting from real world inspired models, or to create altogether new objects. An example is a model originally designed by Claude Cadoz in GENESIS, which physically models wind-like sounds.

Wind-like sounds can be easily obtained in GENESIS by creating a string and replacing the spring interactions of the string by buffer-spring collision interactions. The sound resulting of the numerous and erratic collisions when the structure is excited is akin to white noise [5]. This rich vibratory behaviour can then be used as an excitation mechanism for another vibrating structure. In this case, the wind that our first structure generates "blows" via viscosity interactions on four different non-linear oscillators.

In order to interact with this physical system one can wonder which kind of user induced excitation would yield interesting results. Here, we design a 1D LNL friction interaction with the modified string.

Simulation of this model produces rich and natural wind-like sounds, which are driven by bow-like friction using the haptic device (Fig.10). The user is energetically coupled with the instrument. He can explore the effects of his gestures on the continuity of the sound, the resonance of the system, etc. This example goes to show the diversity of physical objects that can be designed and interacted with, and the creative possibilities for sound production.

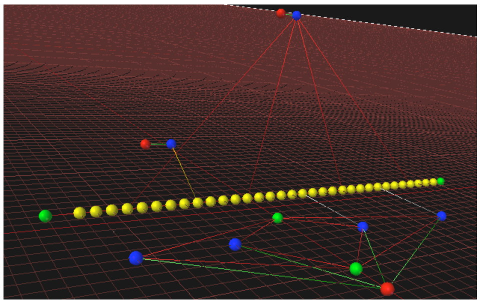

Fig 10. Real Time Haptic Simulation of the bow-driven wind instrument.

8. CONCLUSIONS

In this paper we have presented a first prototype modeller/simulator for musical creation with instrumental interaction. For the first time, GENESIS instruments can be touched, played and experimented with, opening the way for improvisation, exploration and musical learning and creation. By maintaining the energetic link between the user and the instrument we can achieve rich musical interaction, ultimately aiming to recreate a natural instrumental situation.

Furthermore, the modelling/simulation paradigm gives the user full control over his instrument: he can change and perfect its playability and sound over time, change the way he interacts with it, and create instruments that don't or could not exist in the real physical world. As a whole, the ergotic quality of our interactions with simulated instruments opens a vast number of new creative possibilities with GENESIS, which we will continue exploring in the near future.

This first work is a prototype we aim to build upon. Naturally, it is destined to evolve over the next years. We intend to extend our synchronous simulation architecture by introducing multi-frequency models, and upgrade the simulation hardware architecture allowing for much more computing power, resulting in larger and musically richer models such as a 12 key Piano based on the model shown in Fig.8. We also aim to integrate the various TGR end-effectors into our system, as well as extend the complexity of the gesture interaction, by enabling 24 key models connecting several ERGON_X platforms. Finally, our real time haptic simulation features will be integrated into mainline GENESIS.

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